Innovative Approaches to Low Cost Module Manufacturing of String Ribbon Si PV Modules

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ABSTRACT

This paper is a report on the first year of a three year program on a PV Manufacturing R&D sub-contract monitored by NREL. Three advances in manufacturing technology are reported here: a means of doubling String Ribbon output and nearly halving costs; automation through in-line diagnostics; and monolithic module assembly.

1. Introduction

Evergreen Solar is a fully integrated PV module company and is developing innovative manufacturing technology in all three areas: wafers, cells, and module making. In ribbon growth, the project "Gemini", allows for two ribbons to be grown from a single crucible. This has the effect of virtually doubling throughput and halving many costs associated with wafer production. Associated with Gemini are advances in automating the ribbon growth technology, all of which have had the effect of improving productivity. In the module area, advances in making a monolithic module with String Ribbon wrap-around contact solar cells are described as a way to lower module making costs.

2. Gemini – Dual Ribbon Growth

In the conventional String Ribbon process, a ribbon growth machine contains a crucible from which a single ribbon is pulled. The growth of two ribbons from a single crucible within the same growth machine means that many of the consumable costs, much of the capital costs of a machine, and much of the labor costs can be virtually halved. Figure 1 shows the Gemini concept (lower) as well as single String Ribbon growth (top). It can be seen that in the Gemini process, the two ribbons are being grown back to back.

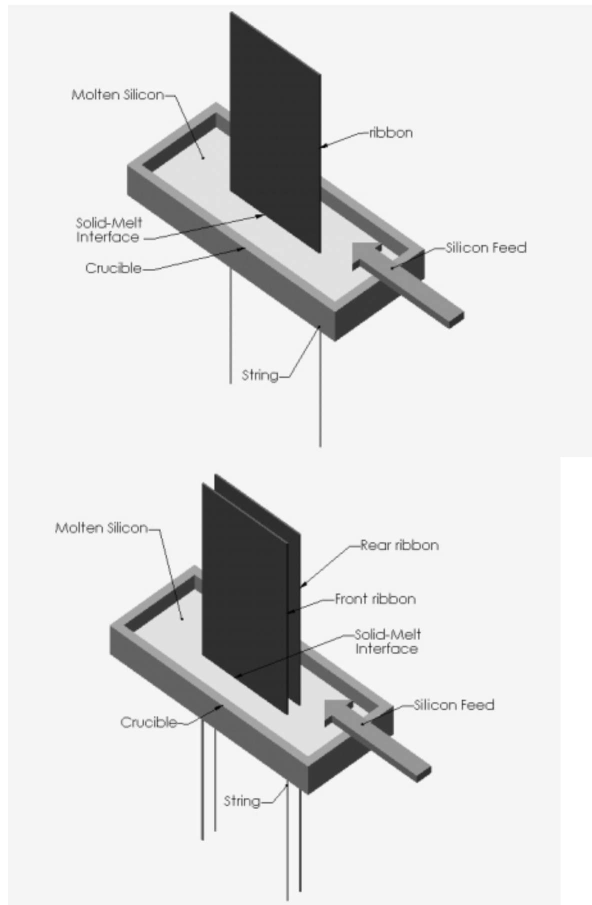

Figure 1 – The String Ribbon process (top) and the Gemini concept (lower).

In the Gemini process, high temperature string materials are still deployed for edge stabilization but now four such strings are in use. Otherwise, the process contains all the advantages of the original String Ribbon technology: i.e., a thermally robust, continuous ribbon process. Advances in afterheater design have allowed us to increase the growth speed of Gemini as well. The net result is that, in principle, a Gemini machine can produce 2.25 times as much ribbon, per unit time, than a single ribbon machine. There were two principal discoveries that paved the way for Gemini. One was a simpler but very effective new design for the afterheater and the other was a novel method to control the meniscus shape for each ribbon.

The entire process and the associated equipment were designed to be compatible with Evergreen's present crystal growth furnaces. In this way Gemini could be retrofit onto the present production machines that produce a single ribbon. A number of such machines have already been retrofitted and are being run in the production area.

3. Gemini Surface Quality
In a previous NREL subcontract, a method that eliminates all need for acid etching prior to p-n junction formation was developed - the so-called "no etch" process. Recent cell data indicates that the as grown surface of Gemini ribbon is at least of comparable quality to that of single ribbon and may possibly be better in terms of the no-etch process. Otherwise, cell quality and grain structure are similar to that of single ribbon.

4. In Line Diagnostics – Crystal Growth Automation
The motivation here was to improve productivity through a more automated Gemini crystal growth system. Three areas are described below: ribbon thickness, crucible thermal control, and melt depth control.

The thickness scanner allows one to measure thickness of the ribbon (continuously across the ribbon, if desired) and was originally developed under an earlier PVMaT subcontract. Here, a number of improvements have been introduced to make the system more robust from a production vantage point. Occasionally, in the past, scanner failures were experienced and were not detected soon enough to allow for corrective action. The thickness scanner now has a self-checking capability and will automatically alert an operator if corrective action is required.

Novel hardware and software were developed to make the thermal adjustment devices used to control crucible melt temperature more robust and with a wider control range. The control system now has a method of periodically calibrating itself.

An improved method for measuring and controlling the depth of the silicon melt has been established. It has reached the point where the sensitivity of the measurement is about 0.001". A new control loop that is able to more effectively handle transients has been added here.

5. In line diagnostics- Laser Cutting Automation
Automated laser cutting/wafer inspection machines are currently used in production. These machines accumulate two meter long strips of string ribbon material as they are harvested from the growth furnaces. They then automatically inspect the strips, cut the ribbons into wafers, inspect the wafers, and sort the wafers into boxes according to the furnace from which the wafer was grown. In line diagnostics at this point include bulk resistivity, flatness, length, and width. Inspection data is displayed on the machines and also uploaded to the factory data system in real time.

After an initial debug period, the machines have run reliably, and have significantly reduced manufacturing cost through the reduction of cutting and inspection labor. Data availability, consistency, and integrity have all been improved markedly. Also, the quality of material passed onto the next manufacturing operation has improved.

6. Monolithic Modules
There are two aspects to this part of the program. One is the development of higher efficiency String Ribbon cells with wrap-around contacts and the other is the use of these cells to form monolithic modules.

Wrap-around contact cells - the original goal for this first year of the program was to make a 12% cell. Improvements have been made in obtaining higher efficiency cells but the principal limitation is still the series resistance of the cells. The 12% goal has been exceeded for a 60 cm^2 cell with a Voc = 0.589 mv., a Jsc = 31.1ma/cm^2 f.f. = .72, and Eff. = 13.1%.

Cells of this efficiency are not obtained all the time and there still is, from a manufacturing point of view, too much scatter in the cell data.

Monolithic Modules - The method of construction of a monolithic module is as follows: Bars of a suitable conductive ink are printed on Evergreen's proprietary backskin material. The module is formed by simply placing the cells with wrap-around contacts on these bars and laminating the entire assembly using Evergreen's proprietary encapsulant material. There is only a single encapsulant layer in front of the cells, and the cells bond directly to the backskin material without any intervening encapsulant layer. The wrap-around contact continues a short distance onto the back of the cell and this portion of it contacts the printed conducting bars on the backskin.

There have been three major technical issues: 1) the cost of the backskin material, 2) a manufacturable process for the lamination procedure, and 3) the integrity of the bond between the base and emitter contacts on the rear edge of the cell and the printed conductive ink bar on the backskin.

Backskin Materials Cost – In order to satisfy all the PV module qualification requirements and also to meet the needs of making a working monolithic module, some modifications to the backskin material were needed, and these added to the overall cost of the material. A possible way to reduce the cost of this material has been found but it is not yet clear that it will satisfy all the qualification requirements, so further work will be needed here.

Manufacturable Lamination Process - Due to the unique structure of a monolithic module, conditions of temperature and pressure are quite different than for conventional PV module lamination. A set of these parameters has been found to work, but reproducibility has not yet been satisfactory, again from a manufacturing vantage point.

Bond Integrity - This bond must perform double duty as both a mechanical bond and a good electrical contact. In order to address all three issues listed above, a useful criterion for the efficacy of a particular monolithic module making procedure is that of an accelerated test utilizing thermal cycling. The thermal cycling is done in an environmental chamber and the modules are cycled between -40°C and +90°C four times over a 24 hour period. At Evergreen a useful time saving procedure has been developed whereby a prototype monolithic module is made using resistance test pattern cells and the series resistance of the entire module is measured as a function of thermal cycling.

Figure 2 shows results for four test modules made with two different lamination temperatures, 180°C and 155°C. The two modules with the lowest values for the series resistance are the higher temperature laminated modules. The significance of these results is that quite small changes in series resistance are taking place – on the order of 10 milliohms for nearly 200 cycles. Earlier calculations had indicated that an increase of 10 milliohms would correspond to a power drop of only 1% for a 50W size monolithic module. It should be noted that the qual tests for PV modules require that there be less than a 10% drop in power as a result of exposure to 200 thermal cycles.

Therefore, it is reasonable to conclude that this method for making monolithic modules could be successful from the point of view of long term reliability.

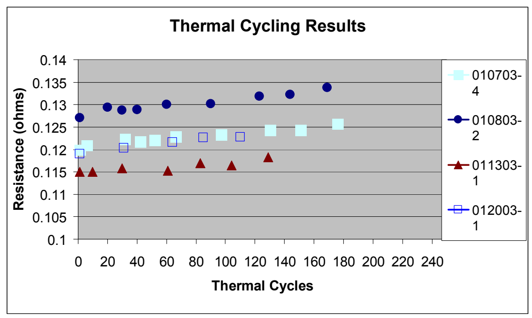

Figure 2 – Change in series resistance for four prototype monolithic modules as a function of thermal cycling.

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